Object-Oriented MDAO Tool with Aeroservoelastic Model Tuning Capability

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Objectives

- Support the Aeronautics Research Mission Directorate (ARMD) guidelines at NASA's Dryden Flight Research Center.
  - Supported by Subsonic Fixed Wing (SFW) & Supersonics (SUP) projects under Fundamental Aeronautics (FA) Program

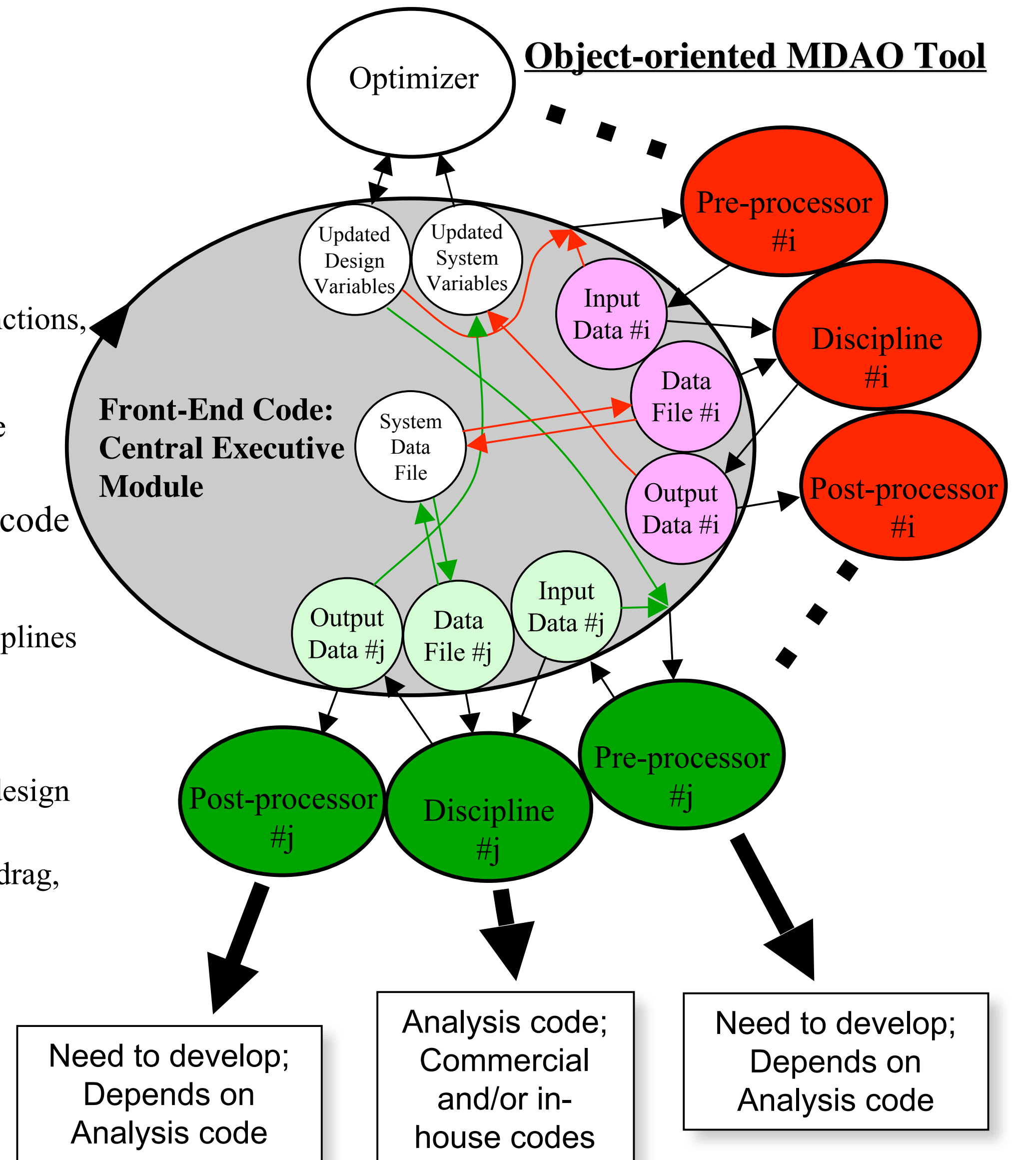
- Generating the basic object-oriented framework for a multi-disciplinary analysis and design optimization tool to be used in the preliminary design stage of a subsonic / transonic / supersonic / hypersonic aircraft.
  - Develop analysis modules for flutter optimization in transonic flight regime
    - No commercial MDO code exists in this speed regime
  - Difficulties in domain of analysis for each disciplines
    - Frequency-domain: Design, Classical control theories, Lifting surface theories, Linear, etc.
    - Time-domain: Analysis, Modern control theories, CFD, Nonlinear, etc.

- The framework will be set up to integrate analysis codes for multiple disciplines, instead of having one code perform the analysis for all the disciplines. These multiple analysis codes will be integrated using a front end code.

- Reduce uncertainties in the aeroservoelastic model to increase the safety of flight
  - Develop model update techniques based on design optimization to improve analysis/test correlation

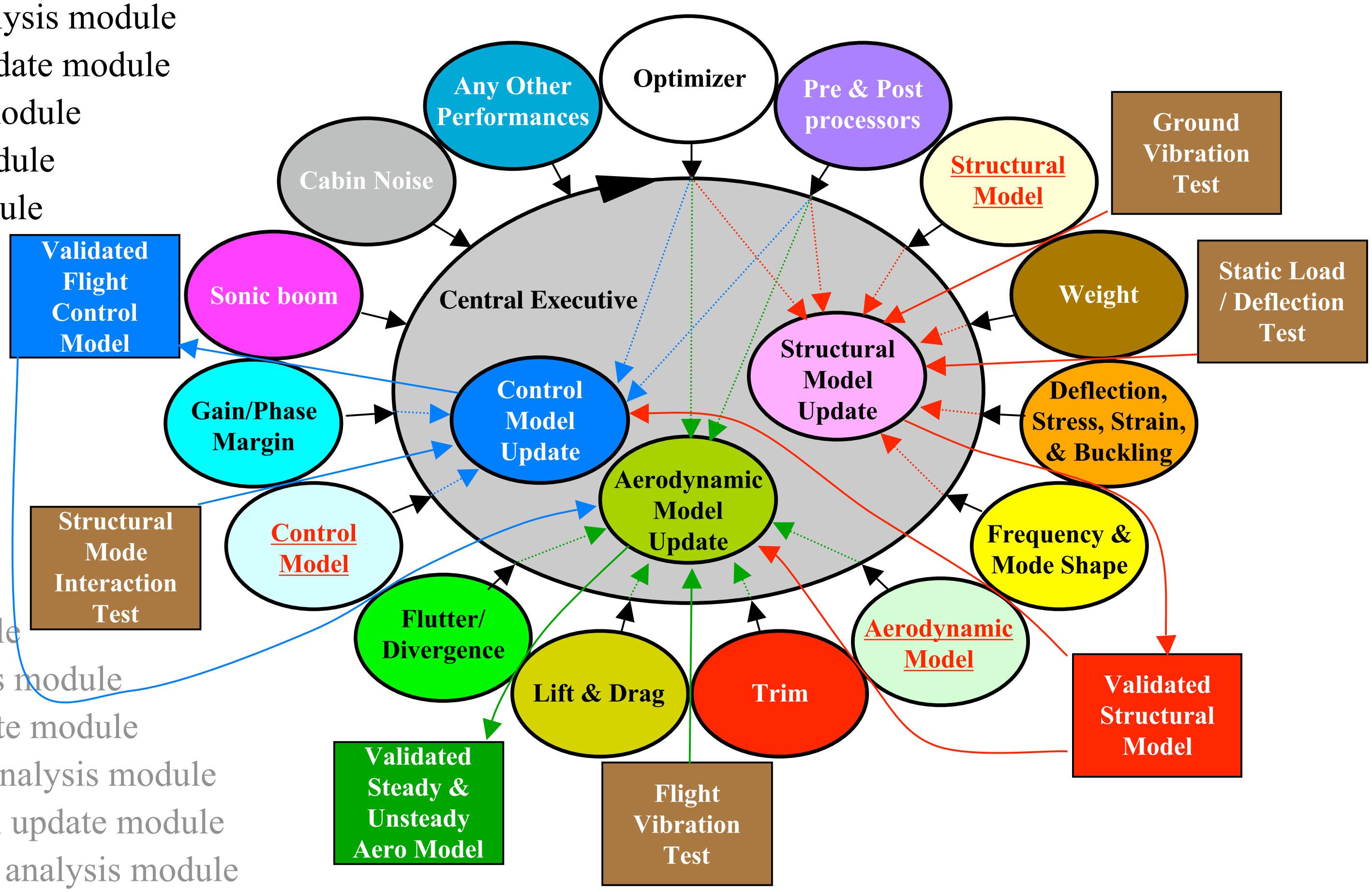
Approach

- ❑ Front-End Code
  - ❖ Based on FORTRAN "call system" command
  - ❖ Optimizer
    - ➢ Genetic Algorithm: gradient free approaches
    - ➢ DOT: based on gradient values
  - ❖ Executive Pre- & Post-processors
    - ➢ Pre-processor
      - ✓ Select optimizer, design variables, objective functions, and constraints
    - ➢ Post-processor
      - ✓ Optimization histories & active constraints table
- ❑ Each Disciplines
  - ❖ Pre-processor: Prepare input data for an analysis code
    - ➢ Read before optimization
      - ✓ Analysis code name
      - ✓ Temporary data file name created by other disciplines
      - ✓ Code name for updating input data
    - ➢ Read during optimization
      - ✓ Read updated values of design variables
      - ✓ Update input data automatically based on new design
  - ❖ Output
    - ➢ System variables (such as total weight, frequencies, drag, noise level, flutter speed, etc.)
    - ➢ Design sensitivity matrices if available
    - ➢ Temporary data file required by other disciplines
  - ❖ Post-processor
    - ➢ Draw results using GUI
    - ➢ Create result data file



Disciplines

- The following modules will be developed in the MDAO code.
  - Flutter/Divergence analysis module
  - Static structural analysis module
  - Structural model update module
  - Buckling analysis module
  - Weight analysis module
  - Modal analysis module



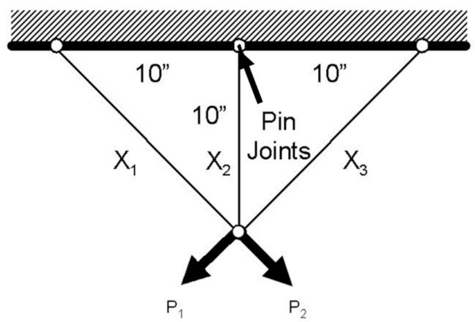
  - Trim analysis module
  - Sonic boom analysis module
  - Control model update module
  - Aerodynamic load analysis module
  - Aerodynamic model update module
  - Gain/Phase margins analysis module
  - Other performance analysis modules, such as cabin noise, mission analysis, landing and taxiing analysis, panel flutter analysis, hot structure dynamics, etc.

Analysis Codes for each Discipline

Disciplines	Analysis Codes		
	FY 08	FY 09	FY10
Stress/Strain Analysis	NASTRAN sol 101		In-house code
Buckling Analysis	NASTRAN sol 105		
Modal Analysis	NASTRAN sol 103		In-house code
Lift, Drag, Trim Analysis		FUN3D	ZAERO, DLM, & KFM
Subsonic/Supersonic Flutter Analysis	ZAERO	DLM	KFM
Subsonic/Supersonic Divergence Analysis	In-house code		
Gain/Phase Margin Analysis		In-house code	ZAERO
Transonic Flutter Analysis in Frequency-Domain		In-house code	
Transonic Flutter Analysis in Time-Domain		FUN3D	
Transonic Aeroservoelastic Analysis in Time-Domain			Modify FUN3D

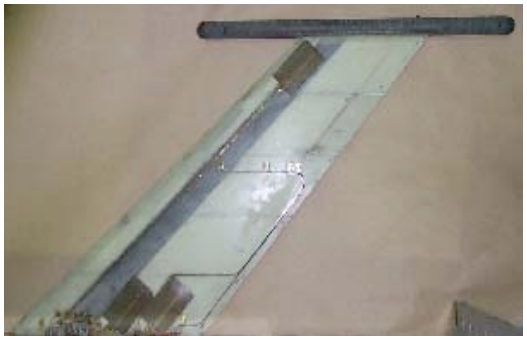
Validations

- ❑ Sample 1: Weight minimization
  - ❖ Three bar truss



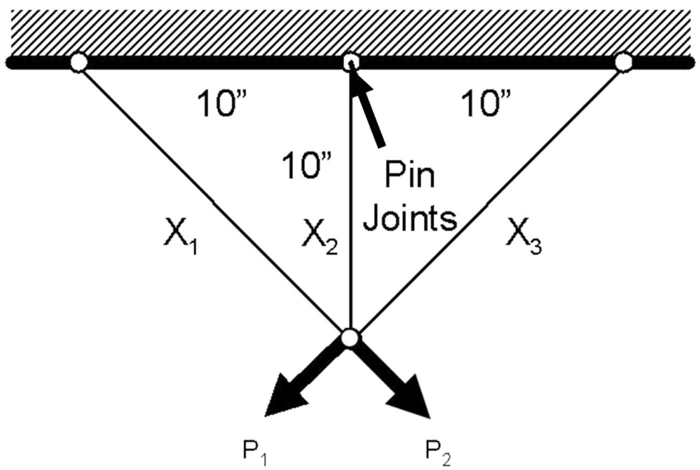
- ❑ Sample 2: Flutter/Divergence speed maximization
  - ❖ NASA 870 IKHANA Aircraft

- ❑ Sample 3: Minimize errors between test data and analytical results
  - ❖ Structural model update
  - ❖ Aerostructures test wing 1



Sample 1: Weight Minimization

- Three Bar Truss Problem
  - Check feasibility of our proposed approach
  - Test weight analysis module
  - Test static structural analysis module



- Objective Function: Minimize total weight

- Applied Load P_1=P_2= 20000 lb

- Constraints
  - Allowable stress 20000 psi (tension)
  - Allowable Stress -15000 psi (compression)

- Design Variables
  - Cross Sectional Areas $X_1 = X_3$ and X_2

Sample 1: Results

- Closed form solution

Assume: $X_1 = X_3$

Objective Function: $f(X_1, X_2) = 2\sqrt{2}X_1 + X_2$

Active Constraint: $\dfrac{2X_1 + \sqrt{2}X_2}{2X_1(X_1 + \sqrt{2}X_2)} = 1 \quad \rightarrow \quad X_2 = \dfrac{2X_1 - 2X_1^2}{\sqrt{2}(2X_1 - 1)}$

$$f(X_1) = 2\sqrt{2}X_1 + \frac{2X_1 - 2X_1^2}{\sqrt{2}(2X_1 - 1)}$$

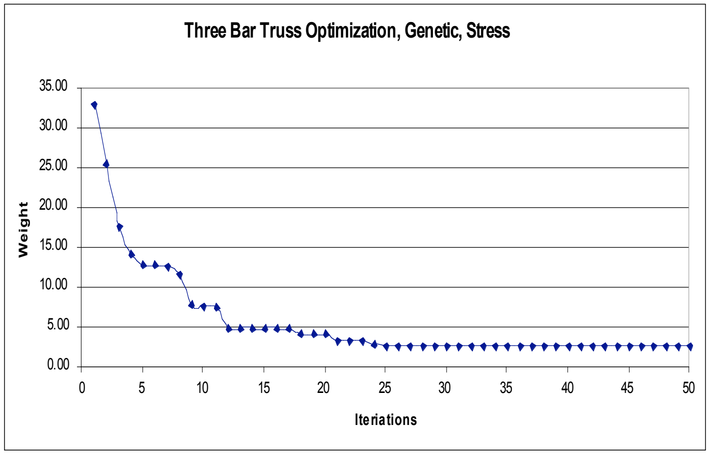
$$f'(X_1) = \frac{\sqrt{2}(6X_1^2 - 6X_1 + 1)}{(2X_1 - 1)^2} = 0$$

$$X_1 = \frac{6 + \sqrt{12}}{12} = 0.788675$$

$$X_2 = 0.408249$$

$$f = 2.638958$$

	Closed form solution	MSC/ NASTRAN	MDAO with DOT	MDAO with GA
Bar Area X_1	.788675	.77142	.78798	.80460
Bar Area X_2	.408249	.45185	.40999	.36526
Total Weight	2.63896	2.6338	2.6388	2.6419
Number of iterations	N/A	5	7	50 generation & 20 propulsion



- Finite Element Model
  - Use MSC / Nastran SOL200
  - Use 3 CBAR (uniform beam) elements

Sample 2: Flutter/Divergence Speed Maximization

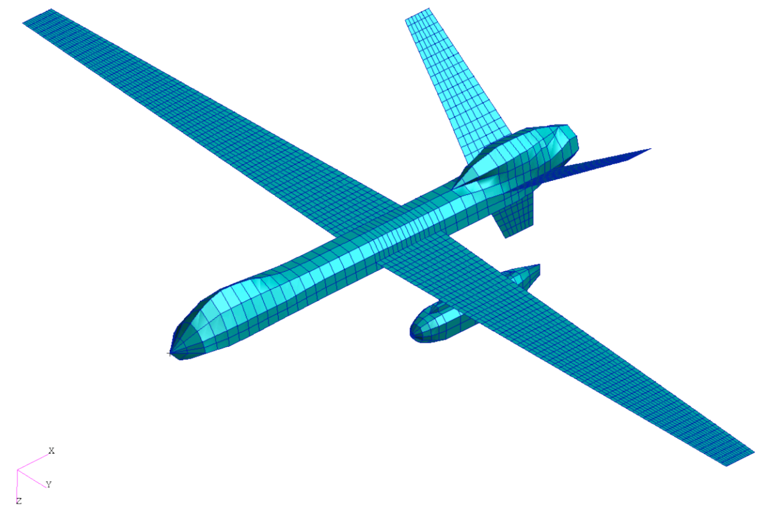
- NASA Dryden Flight Research Center acquired a Predator B unmanned aircraft system for civilian missions.
  - IKHANA carries a ‘fire pod’ that will transmit images of remote areas of the western United States down from the aircraft to a ground station.
  - The fire pod is located under the wing near the left wing root, and can alter the flutter characteristics of the baseline aircraft.
  - Test modal analysis module.
  - Test flutter/divergence analysis module

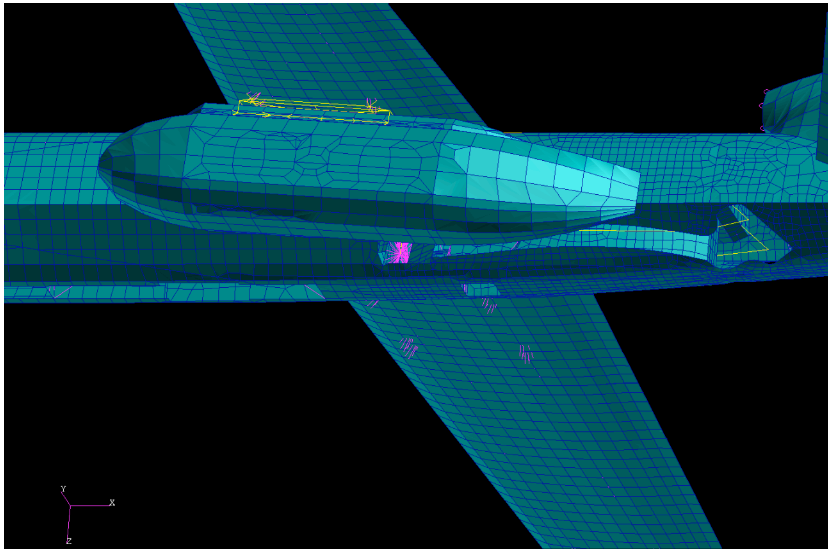
Baseline Configuration

With Fire Pod

Sample 2: Flutter/Divergence Speed Maximization (continued)

- Optimization Problem Statement
  - Objective Function: flutter and divergence speed
  - Constraint: None
- Design Variables
  - Chordwise location of the fire pod
- Structure Finite Element Model
  - MSC Nastran model (18854 nodes and 20979 elements)
- Unsteady Aerodynamic Model
  - ZAERO model (2736 of elements)





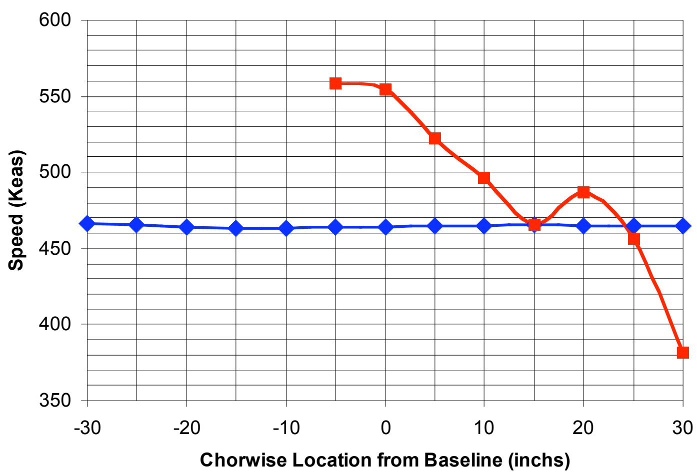
Sample 2: Challenges / Issues

- Modification of the fire pod location affects both the structural finite element model and the unsteady aerodynamic model.
    - New MSC/NASTRAN and ZAERO analyses must be executed for each optimization iteration.
    - Computing speed for generating AIC (from scratch 20 hours; even using existing 30 mins)
    - Genetic optimizer requires thousands of iterations

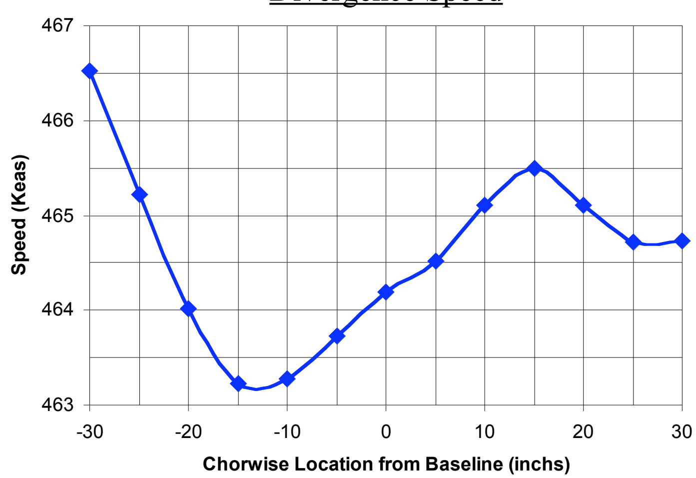
- Approximation Methods
    - Avoid computing a new AIC matrix for each design variable update.
    - AIC approximation based on matrix AJJ (General AIC).
        - ZAERO allows “Direct matrix input” for matrix QHH but not matrix AJJ.
    - AIC approximation based on matrix QHH (Modal AIC).
        - Cubic-spline each element in matrix QHH does not provide accurate estimates. (Mode switch etc.)
    - Flutter and divergence speed approximation based on pre-calculated values.
        - Interpolates flutter and divergence speeds from some pre-calculated flutter and divergence speeds for each design variable update.

Sample 2: Results

Flutter & Divergence Speed



Divergence Speed



Ikhana with fire pod optimization using design optimization tools.

Design variable Chordwise location from baseline, in.		Objective value Critical speed, KEAS
Initial value	Final value	
-20.0	-19.80	463.95
0.0	0.0001	464.20
10.0	14.31	465.53
20.0	14.27	465.53

Summaries of critical speeds before and after optimization using genetic algorithm.

	Design variable Chordwise location from baseline, in.	Objective value Critical speed, KEAS
Baseline	0.00	464.20
Optimized	14.37	465.53

Sample 3: Structural Model Update

- Everyone believes the test data except for the experimentalist, and no one believes the finite element model except for the analyst.
  - Some of the discrepancies come from analytical Finite Element modeling uncertainties, noise in the test results, and/or inadequate sensor and actuator locations.

- MIL-STD-1540C Section 6.2.10
  - Test Requirements for Launch, Upper-Stage, & Space Vehicles
  - Less than *3%* *and* *10%* frequency errors for the *primary* *and* *secondary* modes, respectively
  - Less than *10%* off-diagonal terms in orthonormalized mass matrix

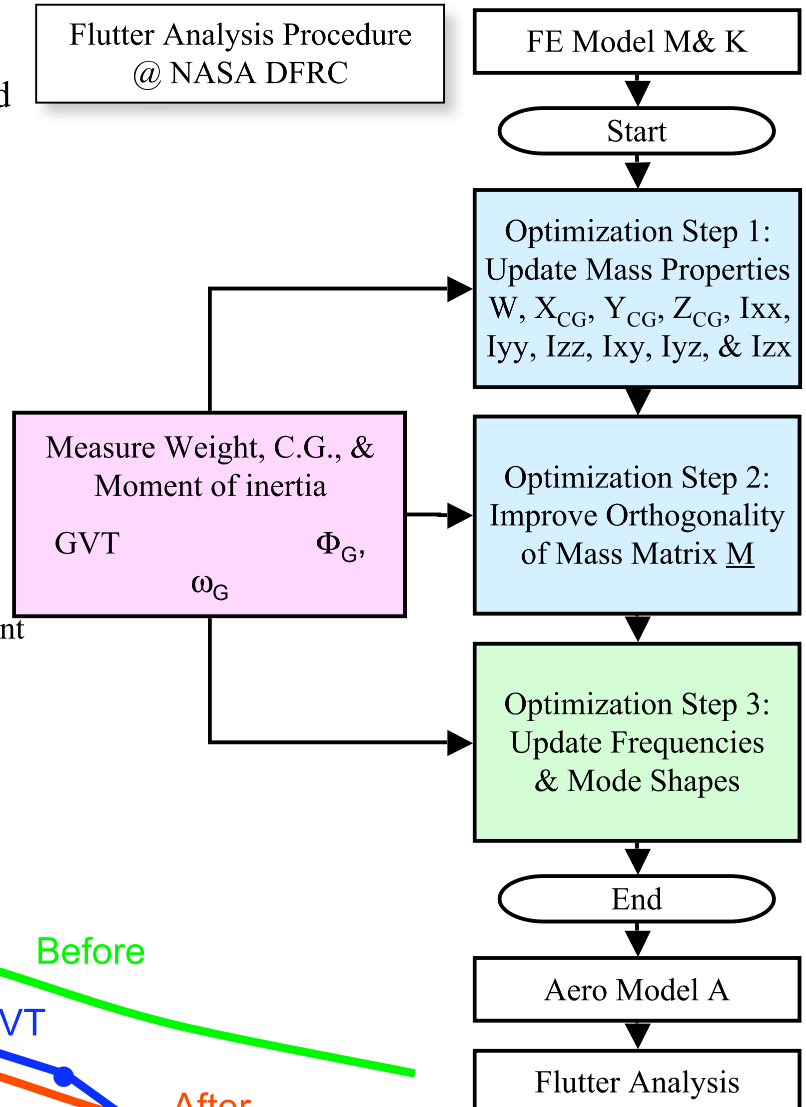
- AFFTC-TIH-90-001 (Structures Flight Test Handbook)
  - If measured mode shapes are going to be associated with a finite element model of the structure, *it will probably need to be adjusted to match the lumped mass modeling of the analysis.*
  - Based on the measured mode shape matrix [F] and the analytical mass matrix [M] , the following operation is performed.

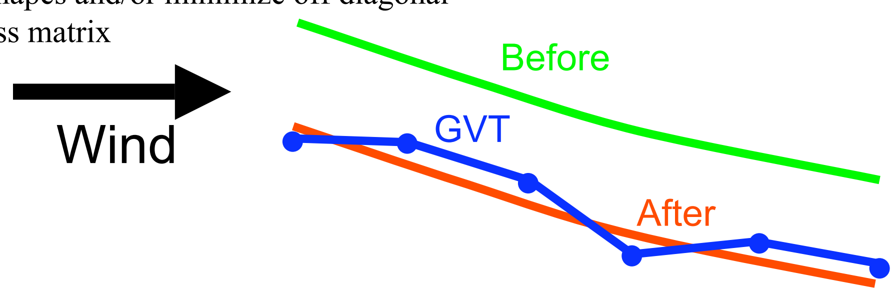
$$\Phi^T M \Phi$$

  - The results is near diagonalization of the resulting matrix with values close to 1 on the diagonal and values close to zero in the off-diagonal terms. Experimental reality dictates that the data will not produce exact unity or null values, so *10 percent of these targets are accepted as good orthogonality* and the data can be confidently correlated with the finite element model.

Sample 3: Structural Model Update (continued)

- Flutter Analysis
  - Uncertainties in the structural dynamic model are eliminated through the use of "model tuning technique"
  - Based on analytical modes
- Update Finite Element Structural Model using Test Data
  - Recall MIL-STD-1540C Section 6.2.10
    - Less than 3% frequency error: primary modes
    - Less than 10% frequency error: secondary modes
    - Less than 10% off-diagonal terms in mass matrix
  - Update Mass
    - Minimize errors in total weight, C.G. location, and mass moment of inertia
    - Minimize off-diagonal terms in orthogonal mass matrix
  - Update Stiffness
    - Minimize errors in frequencies
    - Minimize errors in mode shapes and/or minimize off diagonal terms in orthogonal stiffness matrix





Sample 3: Mathematical Background

- Optimization Problem Statement
  - Minimize J_i
  - Such that $\left|J_k\right| \le \varepsilon_k \quad k = 1 \ldots 13 \quad \& \quad k \ne i$

- Step 1: Improve Rigid Body Mass Properties
  - Errors in Total Mass
  - Errors in CG Locations
  - Errors in Mass Moment of Inertias

Mass Properties	Objective Functions & Constraints
Total Mass	$J_1 = (W-W_G)^2/W_G^2$
CG Locations	$J_2 = (X-X_G)^2/X_G^2$
	$J_3 = (Y-Y_G)^2/Y_G^2$
	$J_4 = (Z-Z_G)^2/Z_G^2$
Mass Moment of Inertias	$J_5 = (I_{XX}-I_{XXG})^2/I_{XXG}^2$
	$J_6 = (I_{YY}-I_{YYG})^2/I_{YYG}^2$
	$J_7 = (I_{ZZ}-I_{ZZG})^2/I_{ZZG}^2$
	$J_8 = (I_{XY}-I_{XYG})^2/I_{XYG}^2$
	$J_9 = (I_{YZ}-I_{YZG})^2/I_{YZG}^2$
	$J_{10} = (I_{ZX}-I_{ZXG})^2/I_{ZXG}^2$

Sample 3: Mathematical Background (Continued)

- Step 2: Improve Mass Matrix
  - Off-diagonal terms of Orthonormalized Mass Matrix: $\underline{\mathbf{M}} = \mathbf{\Phi}_G^{T}\, \mathbf{T}^{T}\mathbf{M}\, \mathbf{T}\mathbf{\Phi}_G$

    Guyan reduction

$$T = T_G = \begin{bmatrix} I \\ -K_{ss}^{-1}K_{sm} \end{bmatrix} \qquad M = \begin{bmatrix} M_{mm} & M_{ms} \\ M_{sm} & M_{ss} \end{bmatrix} \qquad K = \begin{bmatrix} K_{mm} & K_{ms} \\ K_{sm} & K_{ss} \end{bmatrix}$$

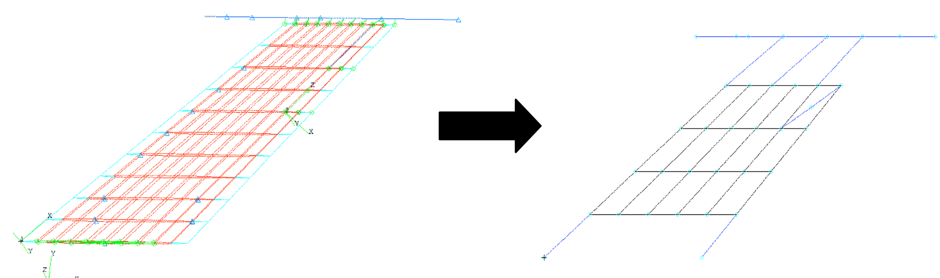
Improved reduction system

$$T = T_{IRS} = \begin{bmatrix} I \\ -K_{ss}^{-1}K_{sm} + (K_{ss}^{-1}M_{ss} - K_{ss}^{-1}M_{ss}K_{ss}^{-1}K_{sm})M_G^{-1}K_G \end{bmatrix}$$

$$M_G = T_G^T M T_G$$

$$K_G = T_G^T K T_G$$

$$J_{11} = \sum_{i=1, j=1, i \neq j}^{n} \underline{M}_{ij}^{2}$$



FEM

GVT

Sample 3: Mathematical Background (Continued)

- Step 3: Frequencies and Mode Shapes
  - Errors in Frequencies

$$J_{12} = \sum_{i=1}^{n} \left(\frac{\Omega_i - \omega_i}{\Omega_i} \right)^2$$

  - Option 1: Off-diagonal terms of Orthonormalized Stiffness Matrix: $\underline{\mathbf{K}} = \mathbf{\Phi}_G^T \, \mathbf{T}^T \mathbf{K} \, \mathbf{T} \mathbf{\Phi}_G$

$$J_{13} = \sum_{i=1, j=1, i \neq j}^{n} \underline{K}_{ij}^2$$

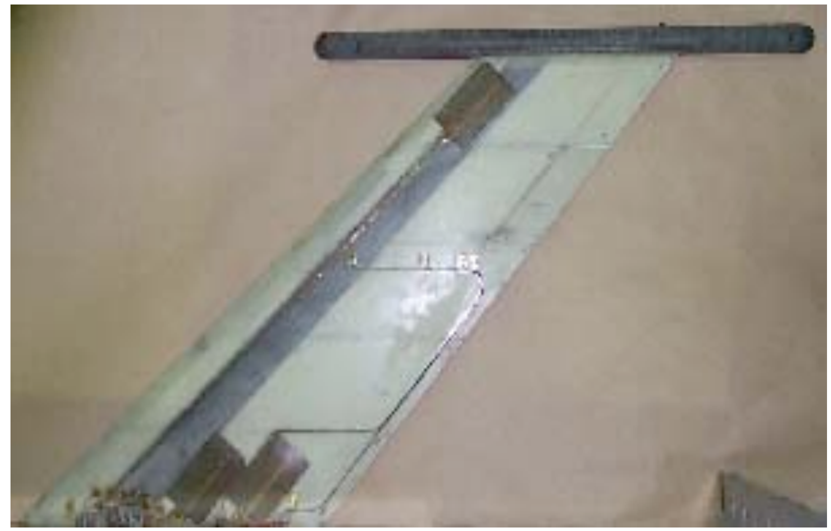
  - Option 2: Errors in Mode Shapes

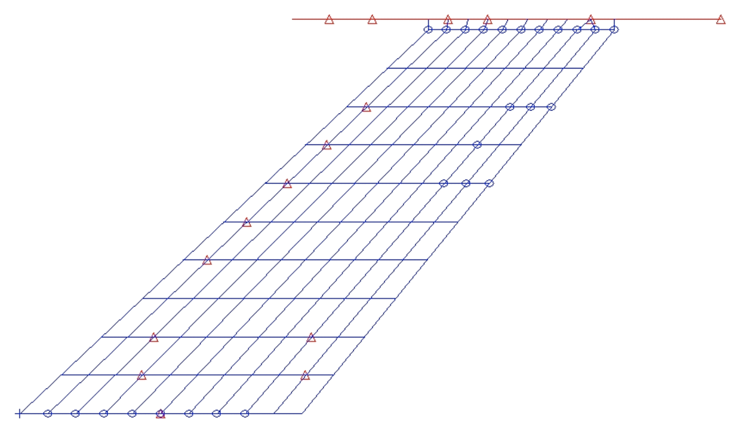
$$J_{13} = \sum_{i=1}^{m} \left(\Phi_i - \Phi_{iG} \right)^2$$

n: number of modes   m: number of sensors

Sample 3: Aerostructures Test Wing 1

Number of DOFs in FE Model	1311
Number of Accelerometers for GVT	35





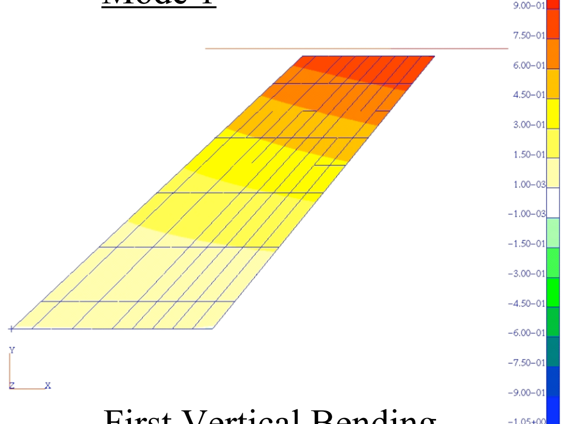
NASTRAN Structure Model

Sample 3: Results

Frequency Comparisons

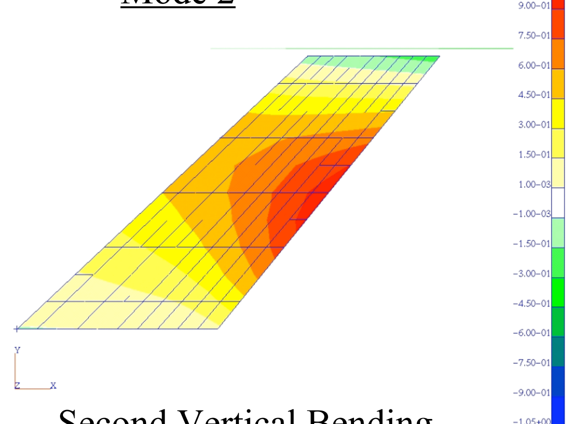
	GVT	Before Optimization (ATA's final)			After Optimization without J_{11}			After Optimization with J_{11}		
	Frequency (Hz)	Frequency/Error (Hz/%)		MAC Value	Frequency/Error (Hz/%)		MAC Value	Frequency/Error (Hz/%)		MAC Value
		Guyan	Full order		Guyan	Full order		Guyan	Full order	
Mode 1	13.76	13.35/-3.0	13.35/-3.0	99	13.75/-0.1	13.75/-0.1	98	13.41/-2.5	13.41/-2.5	95
Mode 2	20.76	22.82/9.9	22.82/9.9	99	20.76/0.0	20.76/0.0	99	21.01/1.2	21.01/1.2	97
Mode 3	77.83	79.06/1.6	78.77/1.2	95	77.82/-0.0	77.84/0.0	95	77.87/0.1	77.50/-0.4	95

Mode 1



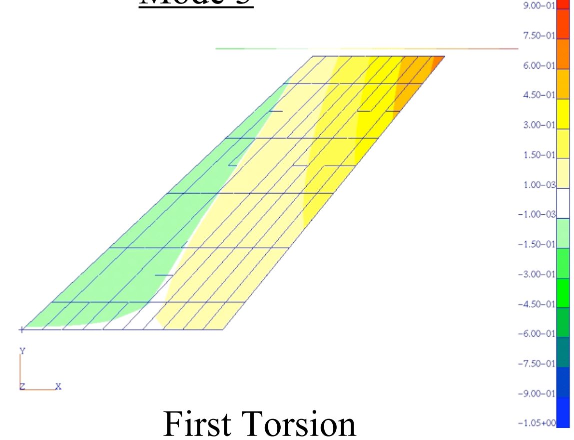
First Vertical Bending

Mode 2



Second Vertical Bending

Mode 3



First Torsion

Sample 3: Results (continued)

Mass Properties

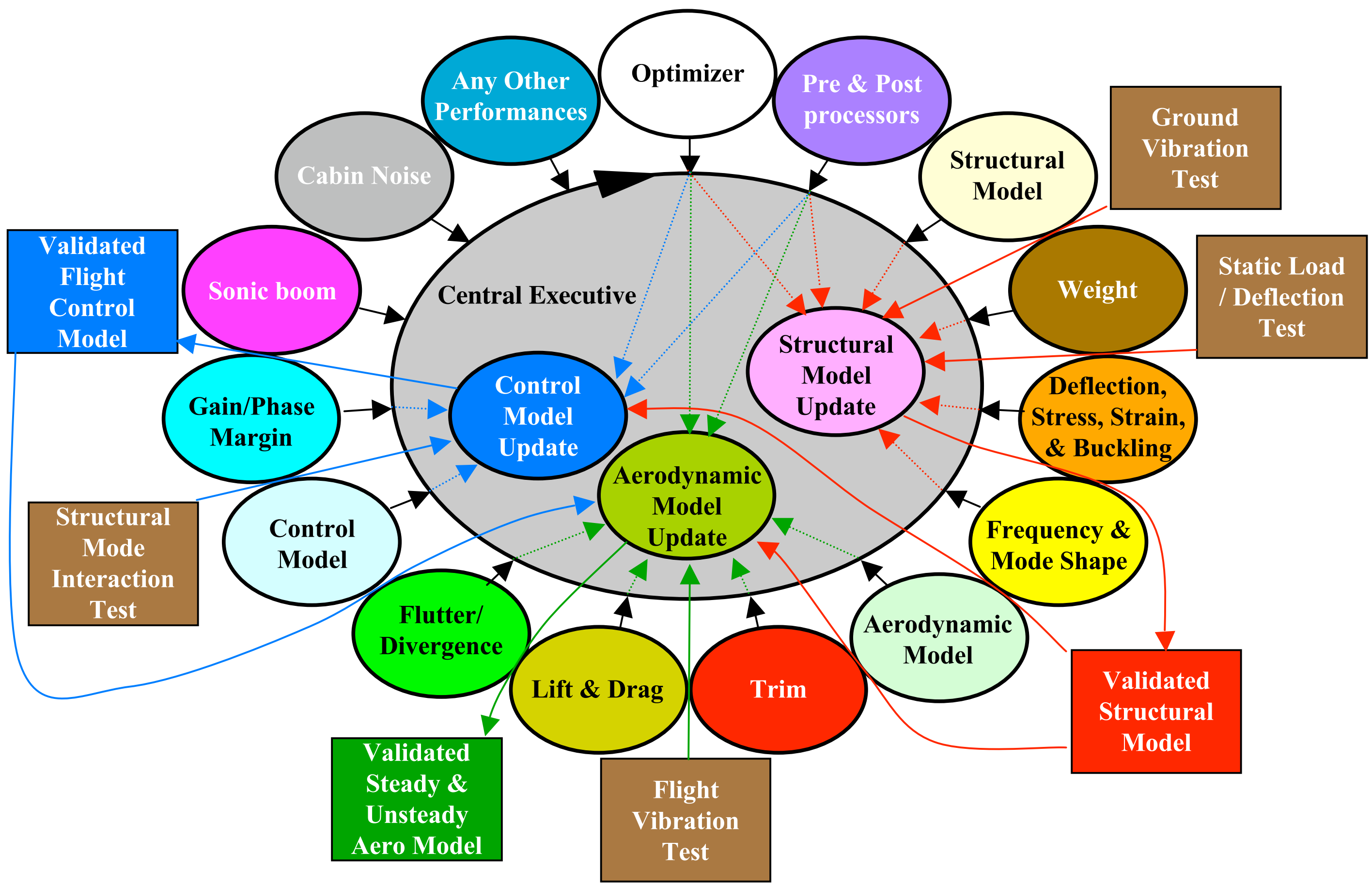
	Measured	Before Optimization	After Optimization without J_{11}	After Optimization with J_{11}
Weight	2.66 lb	2.77 lb (error 4.1%)	2.67 lb (error 0.4%)	2.70 lb (error 1.5%)
X_{CG}	N/A	12.94 inch	12.88 inch	12.72 inch
Y_{CG}	N/A	9.16 inch	8.80 inch	8.91 inch
Z_{CG}	N/A	0.0 inch	0.0 inch	0.0 inch
I_{XX}	N/A	161.22 lb-inch^2	152.06 lb-inch^2	154.78 lb-inch^2
I_{YX}	N/A	95.27 lb-inch^2	93.75 lb-inch^2	89.45 lb-inch^2
I_{YY}	N/A	113.08 lb-inch^2	112.83 lb-inch^2	102.57 lb-inch^2
I_{ZX}	N/A	0.011 lb-inch^2	0.010 lb-inch^2	0.010 lb-inch^2
I_{ZY}	N/A	-0.028 lb-inch^2	-0.035 lb-inch^2	-0.033 lb-inch^2
I_{ZZ}	N/A	268.2 lb-inch^2	258.79 lb-inch^2	251.26 lb-inch^2

	Before Optimization			After Optimization without J_{11}			After Optimization with J_{11}		
Orthonormalized Mass Matrix	1	8.9 %	17.7 %	1	15.7 %	14.8 %	1	3.0 %	11.9 %
	.089	1	9.3 %	.157	1	10.9 %	.030	1	2.8 %
	.177	.093	1	.148	.109	1	.119	.028	1

Conclusions

- An object-oriented MDAO tool has been developed at the NASA Dryden Flight Research Center to automate the design and analysis process and leverage existing commercial as well as in-house codes to enable true multidisciplinary optimization in the preliminary design stage of subsonic, transonic, supersonic and hypersonic aircraft.
  - Once the structural analysis discipline is finalized and integrated completely into the MDAO process, other disciplines such as aerodynamics and flight controls will be integrated as well.
- Simple and efficient model tuning capabilities based on optimization problem are successfully integrated with the MDAO tool.
  - More synchronized all phases of experimental testing (ground and flight), analytical model updating, high-fidelity simulations for model validation, and integrated design may result in reduction of uncertainties in the aeroservoelastic model and increase the flight safety.

Questions ?



Optimizer
Any Other Performances
Pre & Post processors
Cabin Noise
Structural Model
Ground Vibration Test
Validated Flight Control Model
Sonic boom
Central Executive
Weight
Static Load / Deflection Test
Structural Model Update
Control Model Update
Gain/Phase Margin
Deflection, Stress, Strain, & Buckling
Aerodynamic Model Update
Structural Mode Interaction Test
Control Model
Frequency & Mode Shape
Flutter/ Divergence
Lift & Drag
Trim
Aerodynamic Model
Validated Structural Model
Validated Steady & Unsteady Aero Model
Flight Vibration Test